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First determination of the *CP* content of $D \to \pi^+\pi^-\pi^+\pi^-$ and updated determination of the *CP* contents of $D \to \pi^+\pi^-\pi^0$ and $D \to K^+K^-\pi^0$

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ABSTRACT

Quantum-correlated $\psi(3770) \to D\overline{D}$ decays collected by the CLEO-c experiment are used to perform a first measurement of $F_+^{4\pi}$, the fractional *CP*-even content of the self-conjugate decay $D \to \pi^+\pi^-\pi^+\pi^-$, obtaining a value of 0.737 ± 0.028. An important input to the measurement comes from the use of $D \to K_S^0\pi^+\pi^-$ and $D \to K_L^0\pi^+\pi^-$ decays to tag the signal mode. This same technique is applied to the channels $D \to \pi^+\pi^-\pi^0$ and $D \to K^+K^-\pi^0$, yielding $F_+^{\pi\pi\pi^0} = 1.014 \pm 0.045 \pm 0.022$ and $F_+^{KK\pi^0} = 0.734 \pm 0.106 \pm 0.054$, where the first uncertainty is statistical and the second systematic. These measurements are consistent with those of an earlier analysis, based on *CP*-eigenstate tags, and can be combined to give values of $F_+^{\pi\pi\pi^0} = 0.973 \pm 0.017$ and $F_+^{KK\pi^0} = 0.732 \pm 0.055$. The results will enable the three modes to be included in a model-independent manner in measurements of the unitarity triangle angle γ using $B^\mp \to DK^\mp$ decays, and in time-dependent studies of *CP* violation and mixing in the $D^0\overline{D}^0$ system.

1. Introduction

Studies of the process $B^\mp \to DK^\mp$, where D indicates a neutral charmed meson reconstructed in a state accessible to both D^0 and $\overline{D}^0$ decays, give sensitivity to the unitarity triangle angle $\gamma \equiv \arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$ (also denoted ϕ_3). Improved knowledge of γ is necessary for testing the Standard Model description of *CP* violation. In a recent publication [1] it was shown how inclusive three-body self-conjugate D meson decays can be used for this purpose, provided their fractional *CP*-even content is known, a quantity denoted F_+ (or F_+^f when it is necessary to designate the specific decay f). Measurements of F_+ for the decays $D \to \pi^+\pi^-\pi^0$ and $D \to K^+K^-\pi^0$ were performed, making use of quantum-correlated $D\overline{D}$ decays coherently produced at the $\psi(3770)$ resonance and collected by the CLEO-c detector. In this Letter a first measurement is presented of the *CP* content of the four-body mode $D \to \pi^+\pi^-\pi^+\pi^-$, again exploiting CLEO-c $\psi(3770)$ data. This fully-charged and relatively abundant final state [2] can be reconstructed with good efficiency by the LHCb detector and hence is a promising mode for improving the determination of γ at that experiment, as well as at Belle II.

The three-body analysis reported in Ref. [1] exploited events in which one D meson is reconstructed in the signal mode and the other 'tagging' meson in its decay to a *CP* eigenstate. The measurement of $F_+^{4\pi}$ presented in this Letter follows the same method, but augments it with other approaches, in particular a complementary strategy in which the tagging modes are $D \to K_{S,L}^0\pi^+\pi^-$, and attention is paid to where on the Dalitz plot this tag decay occurs. In order to benefit from this strategy for the previously studied decays, this Letter also presents measurements of $F_+^{\pi\pi\pi^0}$ and $F_+^{KK\pi^0}$ using $D \to K_{S,L}^0\pi^+\pi^-$ tags. Throughout the effects of *CP* violation in the charm system are neglected, which is a good

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assumption given theoretical expectations and current experimental limits [2–4]. However, as discussed in Ref. [5], knowledge of F_+ also allows such D decays to be used to study CP-violating observables and mixing parameters through time-dependent measurements at facilities where the mesons are produced incoherently.

The remainder of the Letter is structured as follows. Section 2 introduces the CP-even fraction F_+, derives the relations that are used to measure its value at the $\psi(3770)$ resonance, and reviews how knowledge of F_+ allows non-CP eigenstates to be cleanly employed in the measurement of γ with $B^\mp \to DK^\mp$ decays. Section 3 describes the data set and event selection. Sections 4, 5 and 6 presents the determination of F_+ using CP tags, $D \to K^0_{S,L}\pi^+\pi^-$ tags and other tags, respectively. In Section 7 combinations of the individual sets of results are performed for each signal mode; for $D \to \pi^+\pi^-\pi^0$ and $D \to K^+K^-\pi^0$ these combinations include the results from Ref. [1]. Section 8 gives the conclusions.

2. Measuring the *CP* content of a self-conjugate *D*-meson decay and the consequences for the γ determination with $B^\mp \to DK^\mp$

Let the amplitude of a D^0 meson decaying to a self-conjugate final state f be written as $\mathcal{A}(D^0 \to f(\mathbf{x})) \equiv a_x e^{i\theta_x}$, where $\mathbf{x}$ indicates a particular point in the decay phase space and θ_x is a CP-conserving strong phase. The amplitude is normalised such that

$$\int_{\mathbf{x}\in\mathcal{D}} |\mathcal{A}(D^0 \to f(\mathbf{x}))|^2 \, \mathrm{d}\mathbf{x} = \mathcal{B}(f), \tag{1}$$

where $\mathcal{B}(f)$ is the branching fraction of the D^0 decay and $\mathcal{D}$ indicates the entire phase space. The D^0 decay amplitude at $\bar{\mathbf{x}}$ is denoted $a_{\bar{x}}e^{i\theta_{\bar{x}}}$, where $\bar{\mathbf{x}}$ indicates the point in phase space reached by applying a CP transformation to the final-state system at $\mathbf{x}$. CP violation in the charm system is neglected, which implies that the $\overline{D}^0$ decay amplitude at $\bar{\mathbf{x}}$ is equal to the D^0 amplitude at $\mathbf{x}$. It is useful to define the strong phase difference $\Delta\theta_x \equiv \theta_x - \theta_{\bar{x}}$.

It is possible to express the CP-even fraction in terms of the decay amplitudes introduced above. Let the CP eigenstates be $|D_{CP\pm}\rangle \equiv (|D^0\rangle \pm |\overline{D}^0\rangle)/\sqrt{2}$ and consider the decay $D^0 \to f$ in terms of these states. The total CP-even fraction of the inclusive decay is defined as

$$F_+^f \equiv \frac{\int_{\mathbf{x}\in\mathcal{D}} |\langle f(\mathbf{x})|D_{CP+}\rangle|^2 \, \mathrm{d}\mathbf{x}}{\int_{\mathbf{x}\in\mathcal{D}} |\langle f(\mathbf{x})|D_{CP+}\rangle|^2 + |\langle f(\mathbf{x})|D_{CP-}\rangle|^2 \, \mathrm{d}\mathbf{x}}, \tag{2}$$

and so

$$\begin{aligned} F_+^f &= \frac{\int_{\mathbf{x}\in\mathcal{D}} a_x^2 + a_{\bar{x}}^2 + 2a_x a_{\bar{x}} \cos\Delta\theta_x \, \mathrm{d}\mathbf{x}}{\int_{\mathbf{x}\in\mathcal{D}} 2(a_x^2 + a_{\bar{x}}^2) \, \mathrm{d}\mathbf{x}} \\ &= \frac{1}{2}\left[1 + \frac{1}{\mathcal{B}(f)} \int_{\mathbf{x}\in\mathcal{D}} a_x a_{\bar{x}} \cos\Delta\theta_x \, \mathrm{d}\mathbf{x}\right]. \end{aligned} \tag{3}$$

Note also that the following relation is always true in the absence of CP violation:

$$\int_{\mathbf{x}\in\mathcal{D}} a_x a_{\bar{x}} \sin\Delta\theta_x \, \mathrm{d}\mathbf{x} = 0. \tag{4}$$

Now consider a quantum-correlated $D\overline{D}$ system produced in the decay of a $\psi(3770)$ meson. One of the D mesons in the system decays to f at the point $\mathbf{x}$, the other to g at $\mathbf{y}$, where in general the phase space of the two decays is different. The amplitude of the latter decay is denoted $b_y e^{i\phi_y}$ in analogy with the terminology used above.

The amplitude of the $\psi(3770) \to D\overline{D} \to fg$ correlated wave-function can be written [6]

$$\mathcal{A}(f(\mathbf{x})|g(\mathbf{y})) = \frac{1}{\sqrt{2}}\left[a_x e^{i\theta_x} b_{\bar{y}} e^{i\phi_{\bar{y}}} - a_{\bar{x}} e^{i\theta_{\bar{x}}} b_y e^{i\phi_y}\right]. \tag{5}$$

The resulting decay probability is then

$$\begin{aligned} &\mathcal{P}(f(\mathbf{x})|g(\mathbf{y})) \\ &\propto \Big[a_x^2 b_{\bar{y}}^2 + a_{\bar{x}}^2 b_y^2 \\ &\quad - 2a_x b_{\bar{y}} a_{\bar{x}} b_y \Big(\cos\Delta\theta_x \cos\Delta\phi_y + \sin\Delta\theta_x \sin\Delta\phi_y\Big)\Big]. \end{aligned} \tag{6}$$

If both D mesons decay to the same final state the probability is divided by two to avoid double counting. This formula can be used to determine the population of quantum-correlated decays either integrated over all phase space or after dividing the phase space into bins.

The number of 'double-tagged' candidates in which one D meson decays to f and the other to g, integrating over the phase space of each decay, is

$$M(f|g) = \mathcal{Z}\mathcal{B}(f)\mathcal{B}(g)\Big[1 - \Big(2F_+^f - 1\Big)\Big(2F_+^g - 1\Big)\Big], \tag{7}$$

where $\mathcal{Z}$ is a normalisation constant common to all decay modes. An important special case, considered in Section 4, is where the tagging-mode g is a CP eigenstate, and $(2F_+^g - 1)$ reduces to ± 1. Section 6 describes an analysis of classes of double-tags where this is not the case.

Alternatively, when the tagging-mode g is a multibody decay, its phase space may be divided into bins. Integrating over the phase space of f results in the following decay probability in bin i of the phase space of g:

$$\mathcal{P}(f|g_i) \propto \int_{\mathbf{y}\in\mathcal{D}_i} b_y^2 + b_{\bar{y}}^2 - \Big(2F_+^f - 1\Big) b_y b_{\bar{y}} \cos\Delta\phi_y \, \mathrm{d}\mathbf{y}, \tag{8}$$

where $\mathcal{D}_i$ indicates the phase space encompassed by bin i. In Section 5 this relation is exploited for the tags $D \to K^0_{S,L}\pi^+\pi^-$.

To understand the relevance of the CP-even fraction in the measurement of the unitarity-triangle angle γ consider the decay of a B^- meson to DK^-, following which the D meson decays to a self-conjugate final state f consisting of three or more particles. The amplitude of the B^- decay is a superposition of two decay paths:

$$\begin{aligned} \mathcal{A}(B^-) = &\mathcal{A}(B^- \to D^0K^-)\mathcal{A}(D^0 \to f) \\ &+ \mathcal{A}(B^- \to \overline{D}^0K^-)\mathcal{A}(\overline{D}^0 \to f). \end{aligned} \tag{9}$$

Following the formalism developed above, the decay amplitude of the D^0 meson at the point $\mathbf{x}$ in the phase space is denoted $a_x e^{i\theta_x}$. The decay amplitude of the B^- meson at this point in phase space is therefore

$$\mathcal{A}(B^-(\mathbf{x})) = \mathcal{A}(B^- \to D^0K^-)\Big[a_x e^{i\theta_x} + r_B e^{i(\delta_B - \gamma)} a_{\bar{x}} e^{i\theta_{\bar{x}}}\Big], \tag{10}$$

where r_B and δ_B are respectively the ratio of moduli and the strong phase difference between the suppressed and favoured B^- decay amplitudes. The resulting decay probability is

$$\begin{aligned} \mathcal{P}(B^-(\mathbf{x})) &\propto a_x^2 + r_B^2 a_{\bar{x}}^2 + 2r_B a_x a_{\bar{x}} \cos(\delta_B - \gamma + \theta_x - \theta_{\bar{x}}) \\ &= a_x^2 + r_B^2 a_{\bar{x}}^2 + 2r_B a_x a_{\bar{x}}\Big[\cos(\delta_B - \gamma)\cos\Delta\theta_x \\ &\quad - \sin(\delta_B - \gamma)\sin\Delta\theta_x\Big]. \end{aligned} \tag{11}$$